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THE BUCKING COIL - AN IMPROVEMENT FOR DIPOLE ROOM TEMPERATURE MEASUREMENTS

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1. INTRODUCTION

During the production of Tevatron dipoles the room temperature measurement of field harmonics plays an important role. As it is a long way from a collared coil to a complete magnet, it is essential to get information about the field quality of the produced coils and even about the field quality expected in the complete magnet at liquid helium temperature, as soon as possible so that corrections can be made in the production line or at an individual magnet early enough. Therefore, the room temperature measurements establish a kind of feedback loop in the production line. The quality of this feedback loop depends on the accuracy and reproducibility of these room temperature measurements and on the amount of correlation between them and the measuring results obtained at liquid helium temperature.

In the following chapters the room temperature measuring procedure used up to now is described briefly. Starting from that procedure, improvements are discussed and a new type of measurement, using a bucking coil system for cancelling the dipole component in the magnet is introduced.

First experiences with this system, being used in the last few weeks, are given.

2.1 A short description of the "old-type" measurement.

The system, which has been used for dipole room temperature measurements so far, is described in The Amateur Magnet Builder's Handbook[1] and elsewhere[2]. The measuring probe consists of 12 equally spaced (Δx = 0.215 inch)loops sitting in one horizontal plane plus a vertical loop (null loop) for adjusting the orientation of the system. All loops are formed by tungsten wire embedded in epoxy. The length of the loops is 295 inches, considerably longer than a collared coil (246.75 inches).

For measuring a magnet the coil system, which is shielded by a stainless steel tube, is inserted into the magnet bore. The magnet is powered with a ~±5A peak-to-peak ac current of 11Hz frequency. After adjusting the probe to a horizontal position with respect to the vertical field direction, by using the null loop, the actual measurement begins.

In the median plane the vertical component of the magnetic induction can be expressed by

$$(1) \quad B_y(x) = B_{y_0} \times \sum_n b_n x^n$$

where x is the coordinate in the horizontal direction given in inches, B_{y_0} is the vertical component at the center and b_n are the normal harmonic coefficients.

A similar relation can be written for the induction integrated along the axial direction, the b_n now representing integral harmonics.

The magnetic flux through the different measuring loops is then:

$$(2) \quad \phi_i(x_i) = \phi_0 \times \Sigma b_n x_i^n$$

with ϕ_0 being the flux through a loop in the magnetic center and the x_i being the individual loop center positions. However, the actual measurement consists of measuring the difference signals of adjacent loops in order to measure the field gradient as a function of horizontal position.

The flux differences are:

$$(3) \quad \left(\frac{\Delta\phi}{\phi_0}\right)_i = \sum_n n b_n \times \Delta x \times x_i^{n-1}$$

with Δx being the distance of the loop centers, indicated above.

Actually the voltages induced by the 11Hz oscillation of the flux differences are measured.

For signal detection an ITHACO lock-in amplifier is used, which measures the amplitudes (proportional to the flux differences) and the phases. The phases are used to separate the in-phase component related to the field produced by the driving current from the out-of-phase component produced by eddy current fields.

The in-phase parts of the signals as a function of position x are fitted to a polynomial with 4 parameters giving the first 4 normal harmonics in the integral field distribution.

2.2 Motivations for an improvement.

The system, as it has been used up to now, delivers the normal harmonics b_n fairly well. The measuring accuracy for the most important harmonics b_1 and b_2 is about ±1 unit ($\times 10^{-4}$). However, there is always a reason for improvement, especially if one once tries to improve the harmonic fluctuations of magnets by using a temporary collar which allows for individual harmonic adjustment.

On the other hand skew harmonics have not been measured at all at room temperature up to now. Looking at results from the Magnet Test Facility (MTF) at liquid helium temperature for some skew moments (Fig. 1 and Fig. 2) we find that the fluctuations for a_1 are rather big. Some of these fluctuations may be due to improper positioning of the coils inside the yoke and may be corrected afterwards. But it is necessary to know what amount of skew quadrupole is already built into the coil and it may be better to correct this part in the coil, in order to reduce forces.

2.3 How to measure skew harmonics.

The vertical field component in the horizontal plane of a magnet is a clean superposition of normal moments as indicated in relation (1). More generally the azimuthal field component at an angle α is

(4) $$B_\alpha = B_0 \times \sum_n (b_n \cos((n+1)\times\alpha) - a_n \sin((n+1)\times\alpha)) \times r^n$$

with the a_n being the skew harmonics and r the radius, here expressed in inches.

Similar to relation (3) the flux differences between the loops in a probe turned by an angle α are therefore

(5) $$\left(\frac{\Delta\phi}{\phi}\right)_i = \Sigma n \times b_n' \times \Delta x \times x_i^{(n-1)}$$

with

(6) $$b_n' = b_n \cos((n+1)\times\alpha) - a_n \sin((n+1)\times\alpha)$$

and x_i now being the loop center positions in the new direction of the measuring plane.

Here the coefficients b_n and a_n are the integral harmonics.

Knowing the b_n from a measurement at $\alpha = 0°$ it is now possible to determine the a_n by measuring at some angle $\alpha \neq 0°$.

At $\alpha = -45°$ we have, for instance

(7) $$\begin{aligned} b_1' &= a_1 \\ b_2' &= -0.707\times b_2 + 0.707\times a_2 \\ b_3' &= -b_3 \\ b_4' &= -0.707\times b_4 - 0.707\times a_4 \end{aligned}$$

Obviously a_1 is measured directly here, but there is no measurement for a_3.

At $\alpha = -22.5°$ we have

(8) $$\begin{aligned} b_1' &= 0.707\times b_1 + 0.707\times a_1 \\ b_2' &= 0.383\times b_2 + 0.924\times a_2 \\ b_3' &= a_3 \\ b_4' &= -0.383\times b_4 + 0.924\times a_4 \end{aligned}$$

All lower harmonics can be evaluated here. However, a fairly accurate measurement of the b_n is required for that.

2.4 The difficulties with the "old-type" measurement.

A measurement of skew moments as described in 2.3 has been tried by rotating the measuring coil inside the magnet by -45° and -22.5°. After some initial encouraging results it turned out, however, that the measurement for the skew harmonics was not accurate enough. Variations of 6 units ($\times 10^{-4}$) for a_1 had been obtained in repeated measurements with magnet No. 220.

The results for individual difference loops indicated that these variations were due to changes in loop area differences or angle differences. It can be seen from the following considerations how such changes can influence the results.

Looking at Fig. 3 where two loops are shown with wire distances d_1 and d_2, with angles δ_1 and δ_2 with respect to a common plane and tilted by α with respect to the field direction, the flux difference in a homogeneous field is:

$$(9)\quad \Delta\phi = \ell\times B\times[\cos(\alpha+\delta_2)\times d_2-\cos(\alpha+\delta_1)\times d_1]$$

with ℓ being the effective length of the field. In a first order approximation this results in

$$(10)\quad \Delta\phi = \ell\times B\times d\times[\frac{\Delta d}{d}\times\cos\alpha-\Delta\delta\times\sin\alpha]$$

At the presence of field distortions $\Delta\phi_h$ we have

$$(11)\quad \Delta\phi = \Delta\phi_h+\ell\times B\times d[\frac{\Delta d}{d}\times\cos\alpha-\Delta\delta\times\sin\alpha]$$

As our task is to measure the field distortions, we have to subtract the corrections indicated in (10) from the measured signals.

Unfortunately these corrections happen to be rather big. The most critical case is that of measuring quadrupole moments. We want to be able to measure b_1 moments down to at least 1 unit ($\times 10^{-4}$). Therefore

$$(12)\quad \Delta\phi_h \geq 1\times 10^{-4}\times\phi_0\times n\times\Delta x = 0.215\times 10^{-4}\cdot\phi_0$$

The corrections indicated in (10) and (11), however, are of the order of $10^{-2}\times\phi_0$.

As long as these corrections, representing differences in areas and angles, are completely stable we do not have any problems, but there are certainly some fluctuations to be expected. In order to be able to measure with an accuracy of 1 unit ($\times 10^{-4}$) we can allow fluctuations of 2.15×10^{-3} of $\Delta d/d$ and $\Delta\delta$ only, which is equivalent to 0.004 mil or 0.0215 mrad.

These requirements are very hard and we easily get beyond these limits if there are considerable temperature changes, pressures on the sides of the tube holding the measuring probe, or unreproducible changes during the transport or movement of the probe. Our difficulties in measuring the skew quadrupole moment mentioned above can be easily explained by these effects.

Relation (11), however, also indicates how we can solve the problem. The corrections are so big because of the big dipole field in the magnet. If we reduce B by a considerable amount the corrections are reduced too and we are less sensitive to changes in these conditions.

Therefore, and according to a suggestion by A.Tollestrup, a bucking coil system was built to buck out the big dipole field of the magnets as far as possible.

2.5 The bucking coil structure.

The coil system designed for bucking out the dipole component of the magnets should be as simple as possible, while being also very homogeneous. Systems with two and three coils have been studied. The two coil system was chosen finally, mainly for reasons of simplicity.

The two coils are placed around the magnet, forming a Helmholtz-type coil system (Fig. 4) which has very small higher harmonics in the region of interest; i.e., within a radius of 1 inch around the center.

Each coil consists of 196 turns of 0.125"×0.125" copper wire arranged in a 14×14 matrix with a cross section of 2.15"×2.071". The centers of the cross sections are located at positions $x = \pm 5.721"$ and $y = \pm 3.289"$, thus sitting at approximately 30° with respect to the horizontal median plane of the magnet. At this position the sextupole component of the body field vanishes. However, there is a small decapole left (-5.3 units) which is close to its maximum at this angle.

Magnets to be measured are inserted into the system from above, using a crane. This is the easiest way to handle the magnets, but it requires enough clearance in the horizontal direction between the magnet and the bucking coil. This is the reason for the wide positions of the coil centers. For the same reason the bucking coil has to be somewhat longer than the magnets. As the body fields of the magnet and the bucking coil are pretty well matched this greater length leads to a bigger axial field integral (by ~4.6%). If it is necessary for some reason to match the field integral instead of the body field one can take out some turns symmetrically.

The coil cross sections as well as their centers have to be very precise and completely stable. Therefore, we tried to build the coils as accurately as possible. The coils are held by aluminum frames sitting on stainless steel bars. The frames, normally open on top, have to be closed with stainless steel clamps during each measurement so that the reproducibility of the coil position is assured. The whole system is placed on stainless steel supports so that the magnetic center is 60 inches above the floor. This limits influences of soft steel buried in the ground. It is also necessary to keep other soft steel parts away from the system by about the same distance.

The sensitivity of the system to positional changes is as follows:

A symmetrical opening in the x-direction (horizontally) by 10 mil to each side results in a change Δb_2 by .6 units. A similar symmetrical change in the vertical direction leads to a change Δb_2 by 1 unit.

Asymmetrical changes are more dangerous. A displacement of the first coil quadrant by 10 mil in x-direction produces harmonic changes of

$$\Delta a_1 = 1.31 \text{ units}$$

$$\Delta b_2 = 0.16 \text{ units}$$

$$\Delta a_2 = 0.25 \text{ units}$$

A displacement of the first coil quadrant by 10 mil in y-direction produces changes of

$$\Delta b_1 = -1.31 \text{ units}$$

$$\Delta b_2 = -0.25 \text{ units}$$

$$\Delta a_2 = \ \ 0.17 \text{ units}$$

Similar changes are obtained by displacing other quadrants.

This means that the positional reproducibility of the bucking coil should be better than 7 mil in each direction. For the y-direction this is easily fulfilled because the coils are sitting on a stable support.

The ends of the bucking coil have been built flat for simplicity (race track-type coil) with a small radius of curvature. Therefore, there is a small negative sextupole of -.8 units due to these ends.

Temperature changes of the bucking coil give negligible effects for the body field harmonics. However, there is an increase in coil length by 0.042 inch ($\sim 2\times10^{-4}$ of the whole length) for a temperature change of 20°F, which is the upper limit of temperature change if the coil is powered with ±5A peak-to-peak. The support frames are allowed to glide on the stainless steel bars in case of that elongation.

The aluminum frames and the stainless steel bars as well as the supports are isolated electrically against each other in order to prevent big eddy current loops through the structure.

The actual harmonics of the bucking coil have been measured by R.Peters, using a 43 inch long Morgan coil system at 6 different axial positions. The combined integral harmonics are as follows (in units):

	normal	skew
n = 1 (quadrupole)	-0.34	-5.00
n = 2 (sextupole)	-1.52	0.71
n = 3 (octupole)	-0.24	-0.35
n = 8 (18-pole)	-0.42	-0.01

The decapole was not measured, but calculated to be -5.3 (normal). However, there is a pretty large skew eddy current quadrupole of -17.22 units. The reason for this may be found in the bucking coil support structure which is not really up/down symmetrical or in the environment of the system. The sextupole eddy current term is 1.36 units (normal). It is believed (and discussed later) that the eddy current terms can be well separated and that the in-phase eddy current part is negligible.

2.6 The operation of the bucking coil system.

It is essential that the magnet and the bucking coil are operated in series so that the phases of the currents are the same. Using the same power supply as for the old-type measurement (±5A peak-to-peak, 36V) we are limited in current to about 0.9A peak-to-peak at 11Hz because of the high inductance (bucking coil 0.466Hy, magnet 0.044Hy) and the resistances (bucking coil ~9Ω, magnet ~5Ω). Although this amount of current is rather low, it does not seem to determine the limit to our measuring accuracy. On the other hand the low current has the advantage of negligible heat production and of a much lower stray field.

Because of the bigger field volume in the bucking field (or the higher number of ampere turns) the stray field of the bucking coil is much higher (by about a factor of 3) than the stray field of a single magnet. It is therefore even more necessary that the signal leads to the measuring coils are twisted in pairs. Where this is not possible - for instance at the switch box - an intensive shielding, using μ-metal was necessary. In spite of that it is necessary to place the rack holding the electronics as far as possible from the magnet system. A fixed place for all measurements of this type is recommended.

For measuring the field the same measuring probe is used as for the old-type measurement. After placing the magnet into the system symmetrically (horizontally and vertically this is achieved automatically by v-grooves supporting the magnet) and closing the stainless steel clamps, the flat coil system is inserted to a fixed position in axial direction. As a first step the probe is aligned to the horizontal plane of the magnet by using the null loop and switching the magnet on only. In the second step the magnet is aligned with respect to the bucking field using the null loop again, with the bucking coil switched on only. In this case the total magnet holding the probe is rotated for alignment.

After these alignment steps the sum of loops 6 and 7 are measured with

the magnet switched on only ($V_M(6+7)$)

the bucking coil switched on only ($B_{BC}(6+7)$)

Later on loops 6+7 are measured for both magnets switched on in difference ($V_{M-BC}(6+7)$). All these numbers are measured in reference to the shunt voltage V_S so that current changes cancel. The numbers are used for a calibration of the amplitude of the harmonics and for a calculation of the relative integrated dipole field strength.

$$(13) \quad \Delta\int B d\ell = \left(V_{M-BC}(6+7)/V_S\right) \Big/ \left(\left(V_{M-BC}(6+7)/V_S\right) - \left(V_{BC}(6+7)/V_S\right)\right) - C_0$$

with C_0 being the field integral of a reference magnet.

All single loops and all differences of adjacent loops are measured with the magnet and the bucking coil switched on so that their fields compensate each other. The loop differences divided by the average of loops 6 and 7 represent the relative gradients then being used for fitting the harmonics.

After this measurement, with the measuring probe in the flat position ($\alpha=0°$), the probe is rotated clockwise (looking from downstream) by 22.5°, using the loops 6+7 as an indicator for the angle, with the magnet switched on only.

The measurements are then repeated in the same manner as above. This second measurement allows to determine the skew harmonics.

2.7 The data reduction and evaluation of harmonics.

The raw data delivered by the measuring procedure are the flux differences divided by the average of the flux through loops 6 and 7.

$$\left(\frac{\Delta\phi}{\phi}(\alpha)\right)_i, \quad i = 1, \ldots 11$$

and the flux through 6+7 divided by the shunt voltage V_S for the three different situations with magnet, bucking coil, magnet and bucking coil powered respectively.

$$\phi_M(6+7)/V_S, \quad \phi_{BC}(6+7)/V_S, \quad \phi_{M-BC}(6+7)/V_S$$

Actually the numbers are gathered and prepared by a µ-processer system designed and programmed by R.Peters.

Before being able to fit the harmonics some corrections have to be made to the data.

We used two different methods up to now, with different corrections.

2.7.1 The general method:

Principally this method is valid for all angles . The final flux differences are achieved by the following formula:

$$(14)\quad \left(\frac{\Delta\phi}{\phi}\right)_{fi}=\left[\left(\left(\frac{\Delta\phi}{\phi}(\alpha)\right)_i\times\cos\alpha-C_{1i}\cos\alpha+C_{2i}\sin\alpha\right)\times C_3(\alpha)-C_{4i}(\alpha)\right]\times C_5$$

$$-C_{6i}(\alpha)+C_{7i}(\alpha)$$

with

C_{1i} = $\Delta d_i/d$ = variations of wire distances in the measuring loops

C_{2i} = $\Delta\delta_i$ = variations of angles of the measuring loops

$C_3(\alpha)$ = $(\phi_{M-BC}(6+7,\alpha)/V_S)/((\phi_{M-BC}(6+7,\alpha)-(\phi_{BC}(6+7,\alpha)/V_S))$

$C_{4i}(\alpha)$ = $\sum_n n\times\Delta x_i\times(b_n^{BC}\cos((n+1)\times\alpha)-a_n^{BC}\sin((n+1)\times\alpha))\times x_i^{(n-1)}$

= contribution from bucking coil harmonics

C_5 = 0.813 = 1/1.23

= factor for conversion of harmonics without iron yoke to numbers with iron yoke, because of increase of dipole field

$C_{6i}(\alpha)$ = $\sum_{n=5}^{\infty} n\times\Delta x_i\times(b_n^{M}\cos((n+1)\times\alpha)-a_n^{M}\sin((n+1)\times\alpha))\times x_i^{(n-1)}$

= contribution of magnet harmonics above n=4. Actually odd and skew harmonics are zero at the average.

$C_{7i}(\alpha)$ = $(i-6)\times\Delta x\times\Delta x\times 2\times 6\times\cos(3\times\alpha)$

= increase of sextupole due to iron yoke (~6 units)

Δx = 0.215 = distance of single loop centers.

For the flat measurements α is equal to zero. For the rotated measurements α is calculated.

$$(15)\quad \alpha = \arccos((\phi_M(6+7,\alpha)/V_S)/(\phi_M(6+7,\alpha=0)/V_S))$$

Principally the corrections C_{1i} and C_{2i} can be measured, C_3 is known from the measurement, C_{4i} are known from the bucking coil measurements alone, C_{6i} are known from measurements at helium temperature, assuming that the higher harmonics stay about the same for all magnets, which is roughly true.

Therefore, the final flux differences can be calculated for each α at which they are measured. In practice, however, there are difficulties to find the corrections C_{1i} and C_{2i}.

It is easily possible to measure them as an average over the whole magnet length by measuring the flux differences at $\alpha = 0°$ and $\alpha = 90°$ in the bucking field only. But in the case where the dipole field is bucked out, mainly the ends of the bucking coil contribute only to a dipole flux. Therefore it is necessary to know the areas and angles in this region and the numbers here may be very different from those averaged over the whole length.

As it is very difficult to find these numbers from a direct measurement we had to calibrate our measurements with the results from magnets which have been measured at helium temperature already.

2.7.2 The direct method:

As it is necessary to calibrate with cold measurements anyway we could use another approach for correction with as few other measurements as possible. The final flux differences in this method are then achieved by the following formulas:

$$(16)\quad \left(\frac{\Delta\phi}{\phi}\right)_{fi} = \left(\left(\frac{\Delta\phi}{\phi}\right)_i - C'_{1i}\right) \times C_3(\alpha) + C_{7i}(\alpha) \quad \text{for } \alpha = 0°$$

$$(17)\quad \left(\frac{\Delta\phi}{\phi}\right)_{fi} = \left(\left(\frac{\Delta\phi}{\phi}\right)_i \times \cos\alpha - C''_{1i}\right) \times C_3(\alpha) + C_{7i}(\alpha) \quad \text{for } \alpha = -22.5°$$

While the corrections $C_3(\alpha)$ and $C_{7i}(\alpha)$ are the same as in 2.71, the corrections C'_{1i} and C''_{1i} are achieved from a calibration using results from cold measurements.

The numbers C''_{1i} are calculated here from rotated measurements at a specific angle $\alpha(=-22.5°)$. Therefore we can expect reasonable results only if we measure at about the same angle. This is the most important difference to the previous method. But our measurements show that the angles are fairly reproducible so that both methods give about the same results.

2.8 The calibration with data from cold measurements.

As mentioned above, a direct calibration by measuring the widths and angles of the different measuring loops was not successful. For calibration we therefore have chosen 10 magnets which have been measured already at liquid helium temperature at MTF. The magnets were dismantled from their yokes and cryostats (that had to be done anyway for other reasons) and then measured in the bucking coil system.

These magnets had not been shimmed between cryostat and yoke so that the quadrupole moments of the collared coils should have remained the same. However, some distrubation of the quadrupole moments is expected due to errors of centering the coils in the yokes.

The first four normal and skew harmonics of these 10 magnets measured at helium temperature are given in Table I. Only the average values of the harmonics are used for calibration. The average values of the 11 relative loop differences representing the raw data of the room temperature measurement are shown in Table II.

After the data processing operation and fitting procedure these data should result in the average harmonics of Table I. This leads to the corrections C_{1i} and C_{2i} for the general method discussed in 2.7.1. The results are shown in Tables III and IV, together with the measured area differences and angles. There is no agreement between both sets of numbers as stated earlier.

In a similar procedure the average harmonics and average loop signals have been used to determine the numbers C'_{1i} and C''_{2i} for the direct method of 2.7.2. The results are shown in Tables V and VI.

With these corrections we calculate the harmonics measured with the bucking coil system (Table VII). Actually these numbers represent the predictions for the harmonics at liquid helium temperature. For simplicity we use here the results of the direct method only as there is not much difference between the results of both methods. These harmonics are compared with those measured in cold magnets (Figs. 5-12).

There is a reasonable agreement for harmonics above the quadrupole (mostly within 1 unit). For the quadrupole moments the differences Δb_1 and Δa_1 are shown on Figs. 13 and 14, where the standard deviations are given too.

The differences can be interpreted as results of an incorrect centering of the coils in the yokes. In that case the standard deviation for the off-center position is 5.3 mil (representing the 10 magnets used for calibration only, which had no off-center shimming) in x-direction and 6.3 mil in y-direction (including also some other magnets which had been through the cold measurements already).

2.9 Some difficulties with the new method.

At the beginning there was some concern about a possible disturbance of our measurements by eddy currents induced in the collars of the magnets because of the high field there. Measurements at various frequencies show (Fig. 15) that in the region of 11Hz the frequency dependence is rather low. A big eddy current skew quadrupole moment can be separated from the data and the change of a_1 as a function of frequency is an indication for that too. However, there is no way for producing such an eddy current quadrupole in the magnet itself. (A sextupole is more likely here.) Therefore, it is believed that these eddy currents are induced in the bucking coil support structure. This should not hurt the measurements because most of the eddy current contribution can be separated at the frequency of 11Hz and the remaining part is just a constant correction.

At very low frequencies the measurements become difficult. This is the reason for some big fluctuations in that region.

Criteria for the quality of the new room temperature measuring method are the reproducibility in repeated measurements for a magnet and the ability of predicting the right harmonics.

The reproducibility is shown in Fig. 16 for magnet No. 220, which serves as a reference magnet now. Most of the harmonics reproduce very well, at a level of ±0.3 units or better. If at all there seems to be a small problem with a_1 (±1 unit).

Some difficulties may be due to the procedure of angle determination. As explained earlier, the angle is determined using loops 6+7 as an angle indicator ($\cos\alpha$) with the magnet powered only. This gives at least a good alignment to the average angle of the whole coil system. However, in the compensated case most of the remaining dipole contribution occurs at the ends of the measuring coil and these ends may be at different angles even if the angle is correct at the average.

Given a good reproducibility the ability of predicting cold harmonics depends on questions of how accurately (for quadrupole moments) the coils are placed into the yoke and how systematic changes of the harmonics are when the magnets are cooled down to helium temperature. In most cases these changes may be predictable, but there seem to be at least some magnets with a very different behavior.

3. SUMMARY AND CONCLUSION

The new procedure of measuring magnets in the bucking coil field gives a good reproducibility for most of the lower harmonics. For the normal harmonics the reproducibility is even better than with the old-type measurements. Although there is less reproducibility for the skew quadrupole moment it is certainly sufficient to filter out bad magnets.

The calibration with 10 magnets which have been through the cold measurements already allows to predict cold results for new magnets. However, a new calibration is necessary later on with magnets which have not been cooled down earlier.

4. REFERENCES

1. A.V.Tollestrup, "The Amateur Magnet Builder's Handbook", UPC No. 86, Feb. 22, 1979.
2. R.E.Peters, L.Harris, J.M.Saarivirta, A.V.Tollestrup, IEEE Trans. Magn., 15, 134 (1979).

TABLE I

RESULTS OF MTF MEASUREMENTS USED FOR CALIBRATION

The units used for the harmonics are 10^{-4} of the dipole amplitude at the center and at a radius of 1 inch.

Magnet No.	b_1	b_2	b_3	b_4	a_1	a_2	a_3	a_4
220	-4.86	-0.88	-2.00	3.85	-4.80	-1.14	-2.23	-0.87
262	3.05	3.92	-0.12	0.54	-0.29	-0.03	-3.12	-0.38
282	-1.17	-0.31	-1.86	-0.29	4.10	1.15	-0.89	0.35
295	4.36	-4.93	-0.74	-3.37	-0.26	0.82	-1.88	-0.27
299	1.22	-4.50	-0.16	-1.62	-0.58	0.12	-1.48	-0.34
300	-0.05	1.10	-1.58	0.74	2.92	-0.26	1.16	-0.41
301	1.86	3.42	-0.35	1.05	3.48	0.30	-0.41	-0.43
304	-1.66	3.29	0.01	0.58	-1.87	-0.15	-1.20	0.15
306	-2.29	2.79	-1.23	1.06	-0.33	-0.18	1.57	-0.84
307	-1.88	-2.71	-1.11	-0.84	0.88	-0.91	0.39	-0.62
Mean value	-0.142	0.119	-0.914	0.170	0.321	-0.028	-0.809	-0.366

TABLE II

AVERAGE SIGNALS OF LOOP DIFFERENCES AT ROOM TEMPERATURE MEASUREMENTS FOR MAGNETS OF TABLE I

The units are 10^{-4} of the average flux through loops 6 and 7.

Loop Differences	$\alpha = 0°$	$\overline{\alpha} = -22.5514$
2-1	-240.96	333.14
3-2	-21.60	62.92
4-3	3.91	-52.89
5-4	-24.38	33.84
6-5	18.62	-44.41
7-6	-15.60	-17.23
8-7	-36.87	-12.46
9-8	39.87	-49.41
10-9	-18.14	22.72
11-10	-39.54	3.96
12-11	348.27	-301.40
$V_M(6+7)/V_S$	3.34798	3.09198
$V_{BC}(6+7)/V_S$	-3.49444	-3.23439
$V_{M-BC}(6+7)/V_S$	-0.152116	-0.145254

TABLE III

CORRECTIONS C_{1i} AND AREA DIFFERENCES

The units are 10^{-4} of the dipole amplitude and 10^{-4} of 1.

Loop Differences	C_{1i}	$\Delta d/d$
2-1	171.55	-64.0
3-2	39.36	-33.4
4-3	12.50	-37.1
5-4	-11.30	-24.1
6-5	29.73	15.7
7-6	-14.82	-16.4
8-7	-47.57	-8.8
9-8	23.71	26.7
10-9	-35.60	-5.6
11-10	-117.47	-3.8
12-11	-91.64	96.8

TABLE IV

CORRECTIONS C_{2i} AND ANGLE DIFFERENCES

The units are $10^{-4}$of the dipole amplitude and 10^{-4} of 1 radian.

Loop Differences	C_{1i}	$\Delta\delta$
2-1	-624.72	-7.3
3-2	-20.05	101.1
4-3	-58.16	-27.8
5-4	193.69	104.0
6-5	-116.21	-35.1
7-6	41.15	76.1
8-7	114.01	111.6
9-8	-175.65	-152.0
10-9	115.94	15.3
11-10	429.15	243.6
12-11	549.56	-117.2

TABLE V

CORRECTIONS C'_{ii}

The units are 10^{-4} of the dipole amplitude.

Loop Difference	C'_{ii}
2-1	-191.64
3-2	22.05
4-3	39.48
5-4	0.92
6-5	31.71
7-6	-16.43
8-7	-53.09
9-8	7.03
10-9	-68.61
11-10	-108.41
12-11	260.47

TABLE VI

CORRECTIONS C''_{ii}

The units are 10^{-4} of the dipole amplitude.

Loop Difference	C''_{ii}
2-1	331.27
3-2	76.41
4-3	-34.94
5-4	41.11
6-5	-35.37
7-6	-15.20
8-7	-16.98
9-8	-59.09
10-9	-2.81
11-10	-33.34
12-11	-331.96

TABLE VII

CALCULATED HARMONICS FROM MEASUREMENTS

USING THE BUCKING COIL SYSTEM

The units used for the harmonics are 10^{-4} of the dipole amplitude at the center and at a radius of 1 inch.

Magnet No.	b_1	b_2	b_3	b_4	a_1	a_2	a_3	a_4
220	-3.6	-2.3	-1.9	1.9	-0.6	-1.0	-2.1	-0.4
262	2.0	3.8	0.1	-0.9	0.0	-0.8	-1.6	-0.2
282	-0.4	-0.9	-0.5	1.6	1.2	1.7	-1.5	0.1
295	2.0	-3.4	-0.7	-2.7	-0.1	0.1	-1.3	-0.2
299	1.4	-3.6	-1.2	-0.3	-0.1	0.7	-0.9	-1.3
300	0.6	1.4	-1.6	0.3	4.2	-0.2	1.2	0.0
301	0.6	2.4	0.3	1.7	1.2	1.0	-1.5	-0.5
304	-0.8	3.1	-0.3	0.5	-3.2	-0.2	-1.2	0.0
306	-2.4	2.6	-1.6	1.0	-1.7	0.3	0.9	-0.9
307	-0.9	-1.7	-1.8	-1.3	2.3	-1.8	-0.1	-0.2

Fig 7
Skew quadrupole moments
(Magnet numbers are indicated)

MTF Results
a_1
68 entries
25 out of limits $\pm 3 \times 10^{-4}$

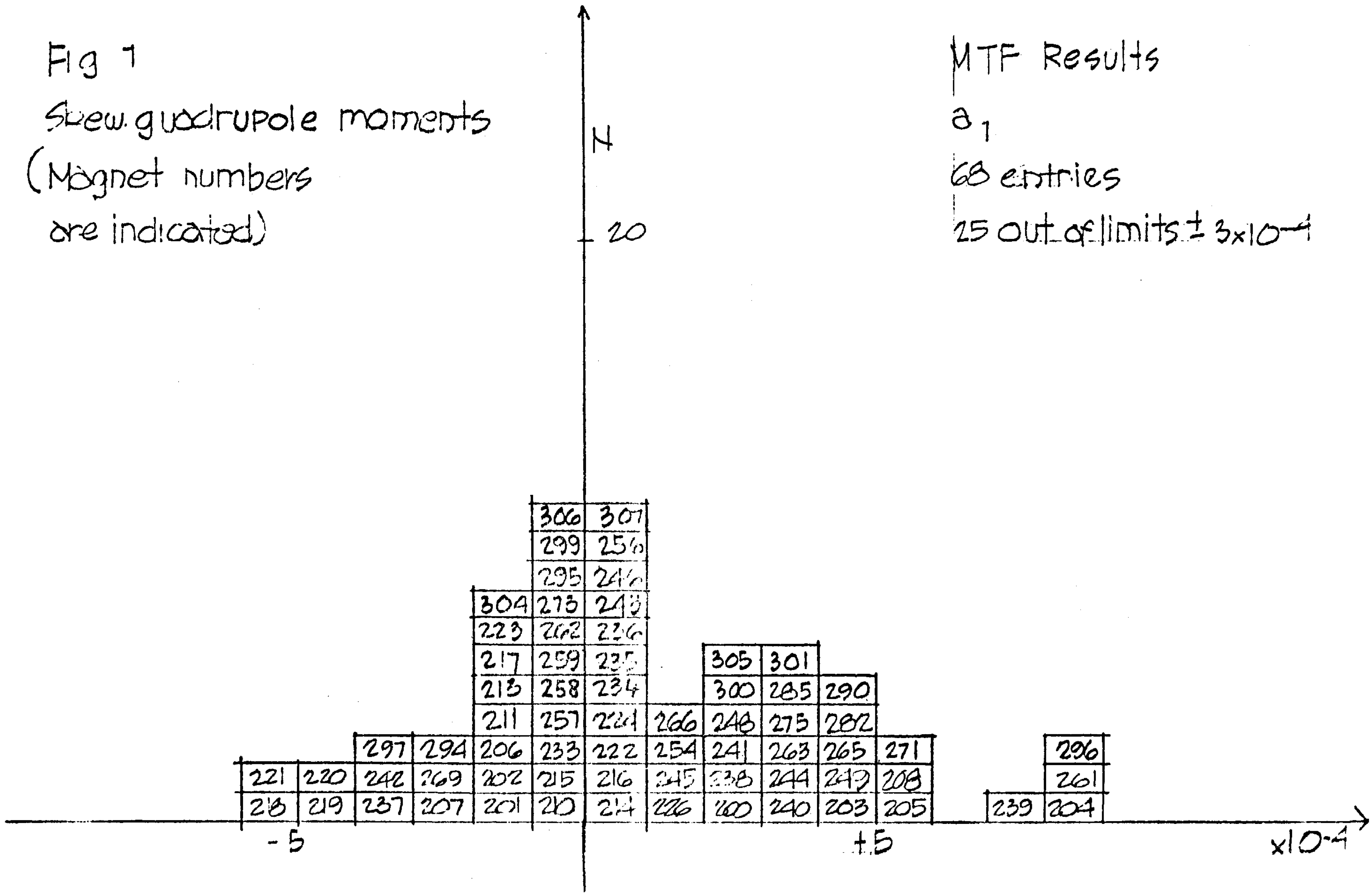


Fig. 2

Skew sextupole moments
(Magnet numbers are indicated)

MTF Results
a_2
68 entries
2 out of limits $\pm 3 \times 10^{-4}$

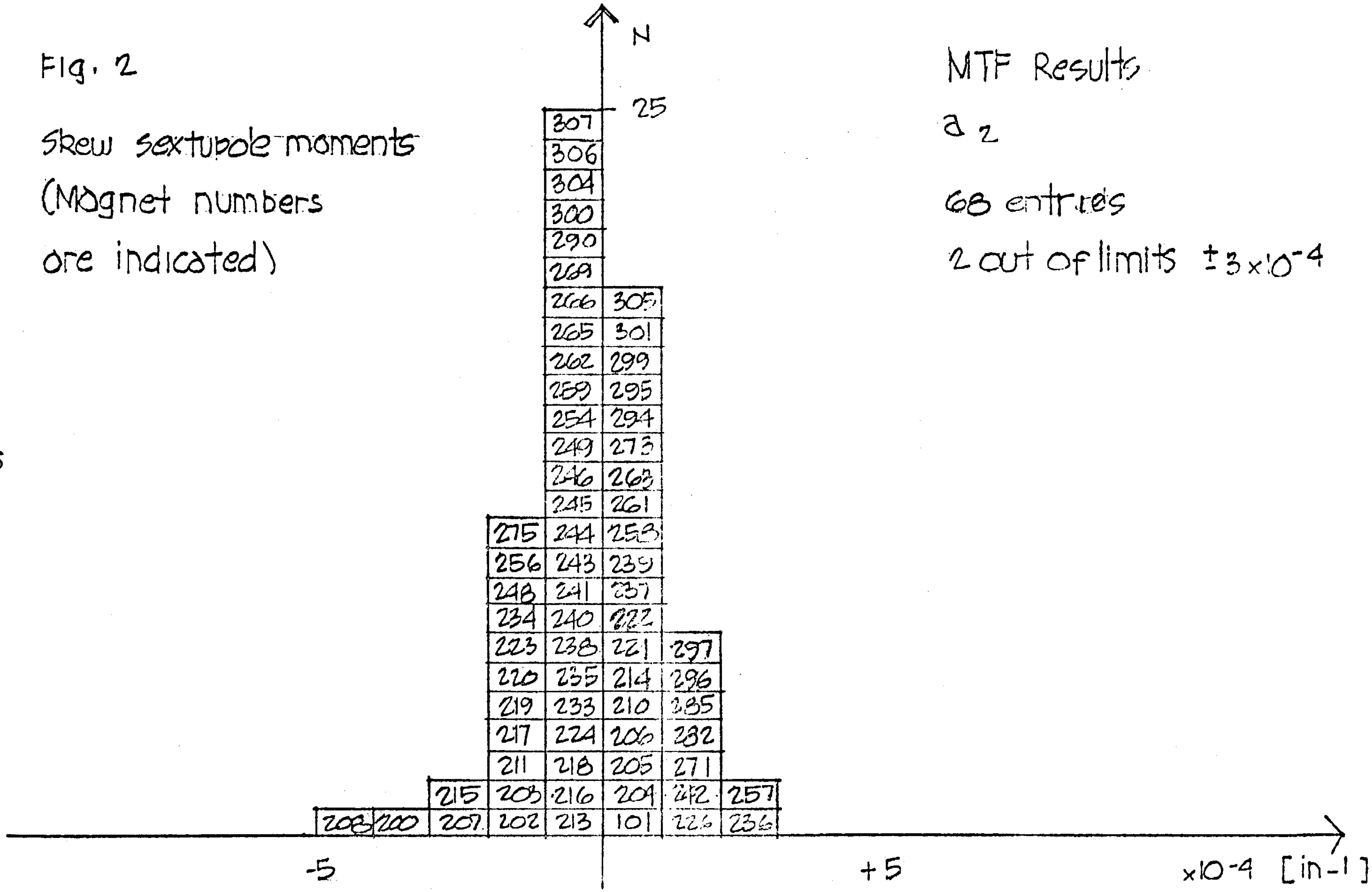
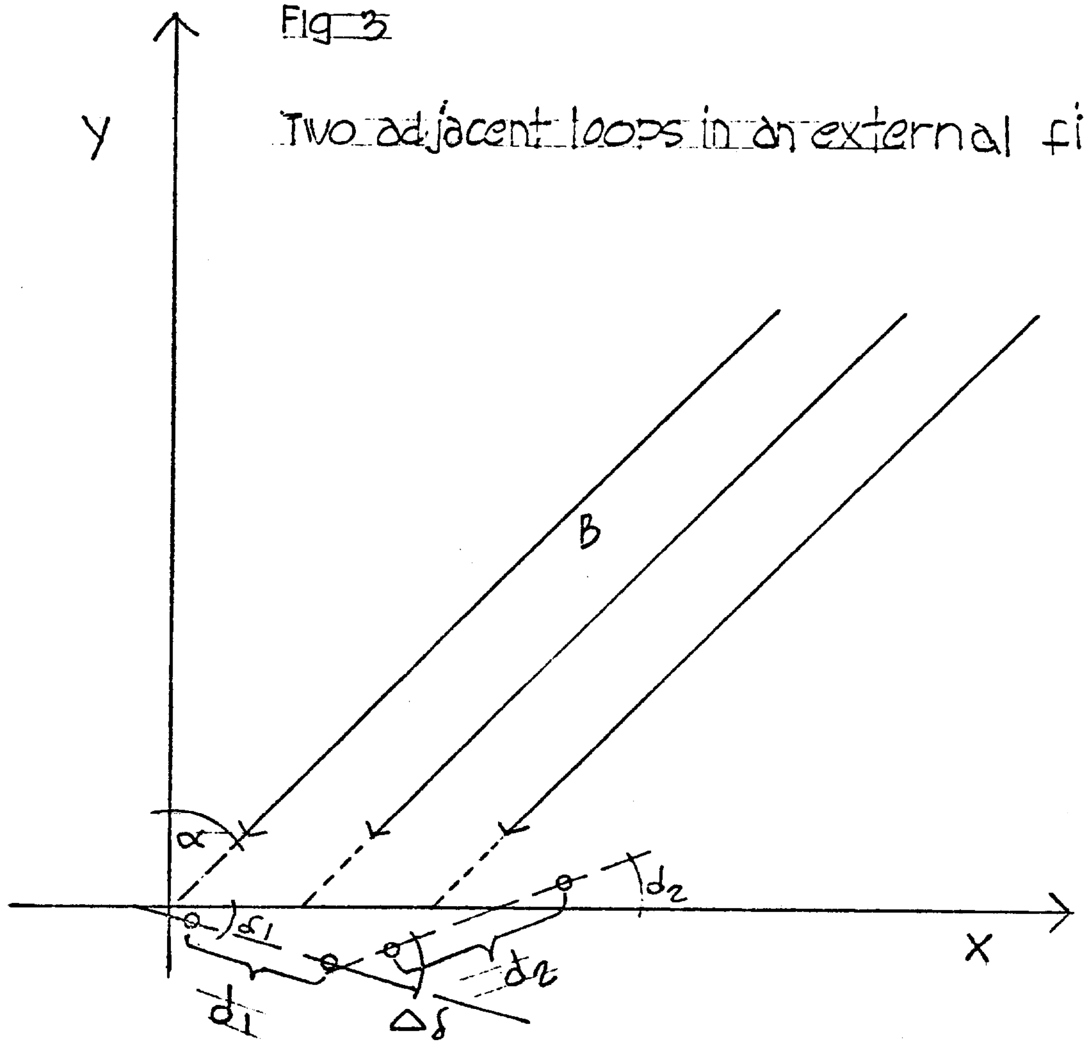


Fig 3

Two adjacent loops in an external field

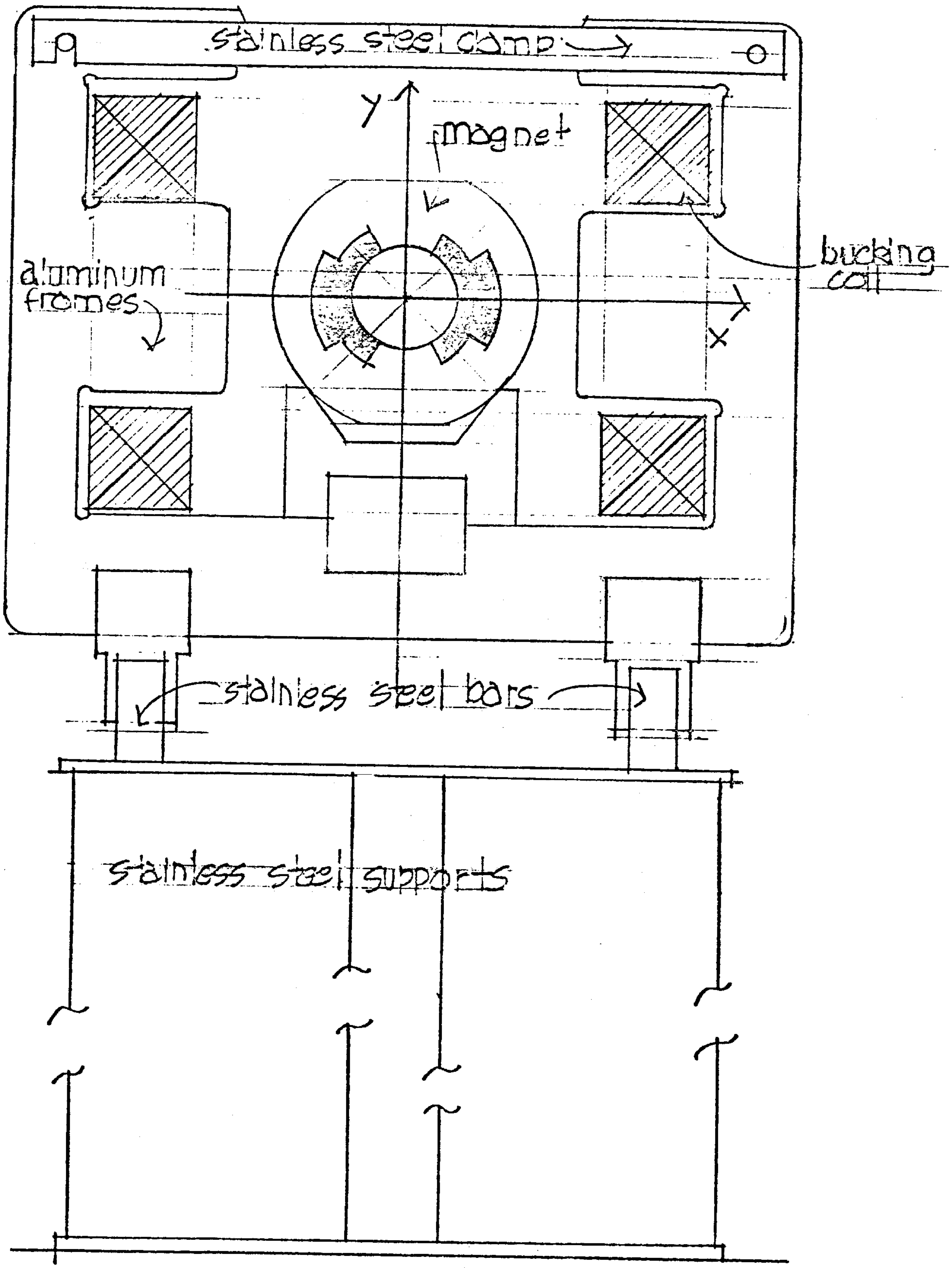


$$\Delta d = d_2 - d_1 \quad , \quad \Delta\delta = \delta_2 - \delta_1 \quad d \approx d_1 \approx d_2$$

$$\Delta\phi = \Delta\phi_h + eB\cdot d\left[\frac{\Delta d}{d}\cos\alpha - \Delta\delta\sin\alpha\right]$$

Fig 4

The bucking coil structure



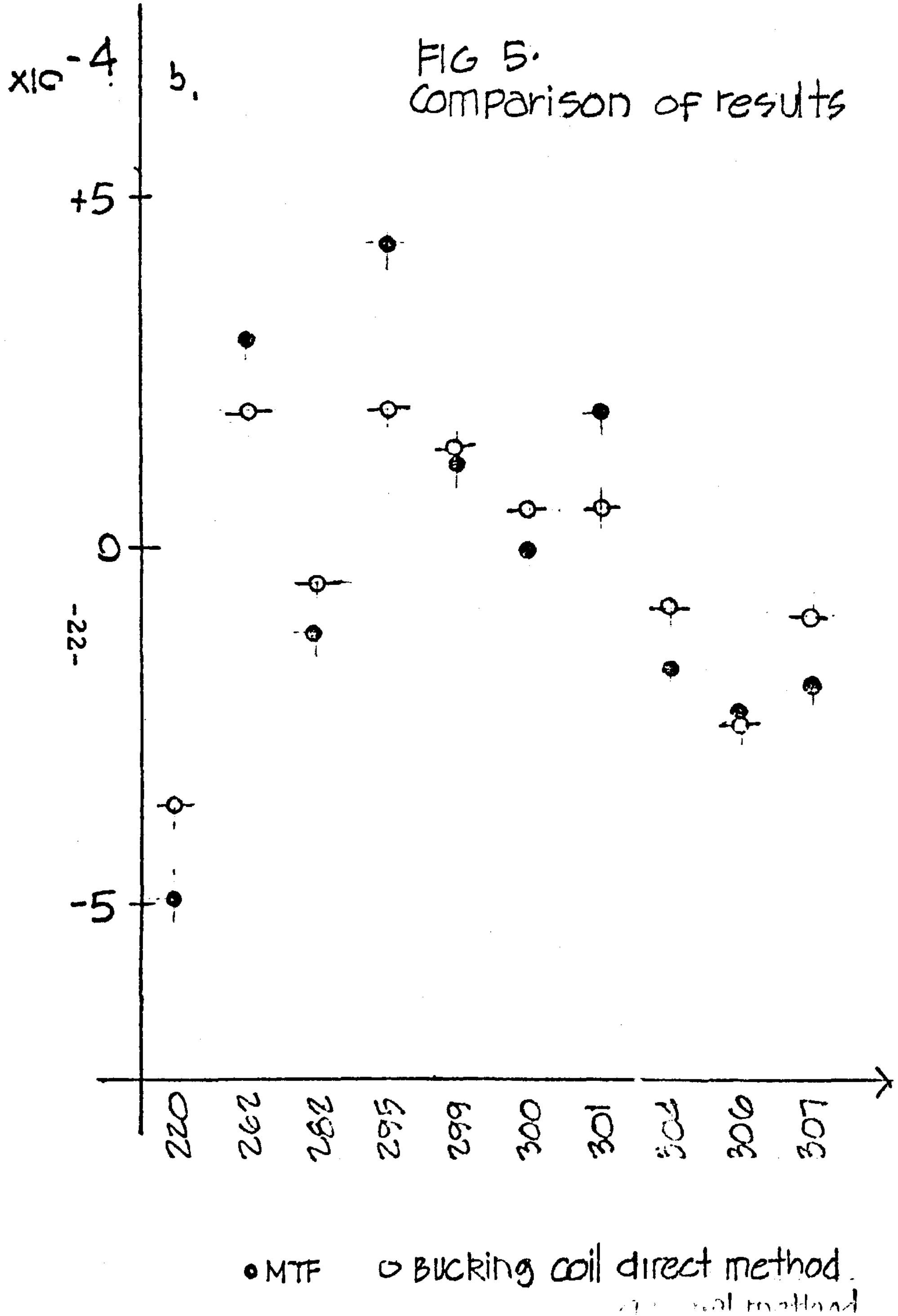


FIG 5. Comparison of results

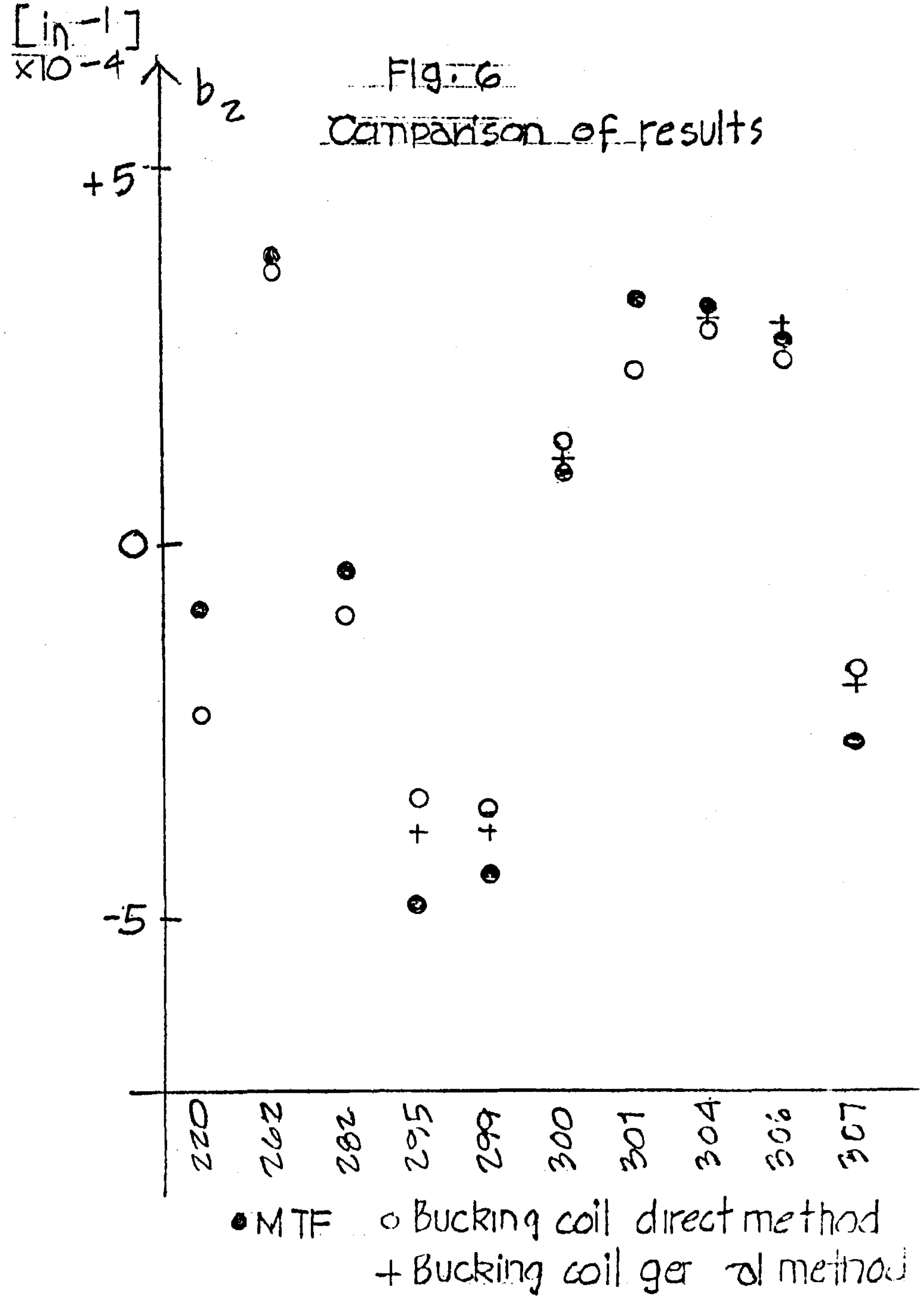


Fig. 6 Comparison of results

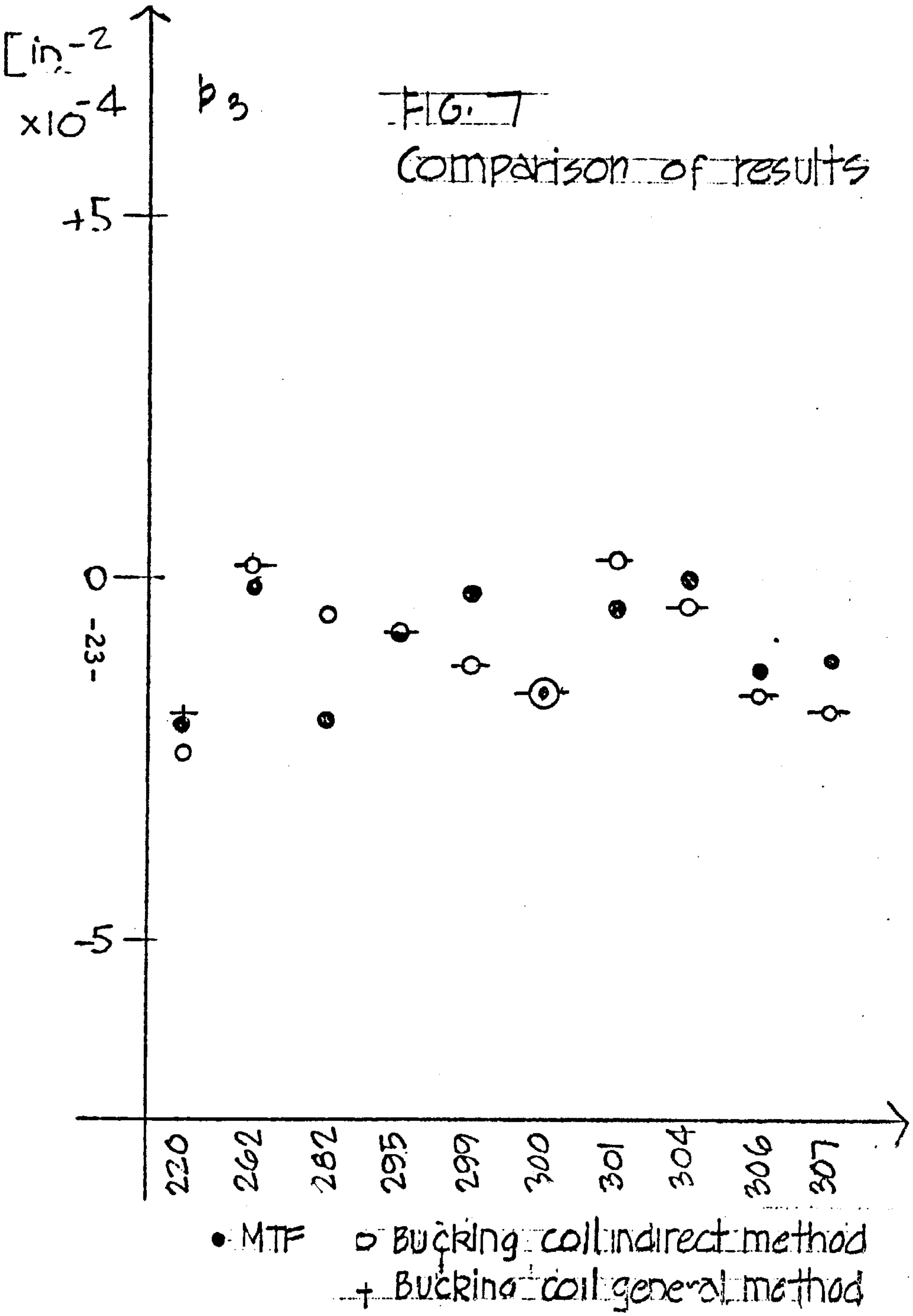


FIG. 7
Comparison of results

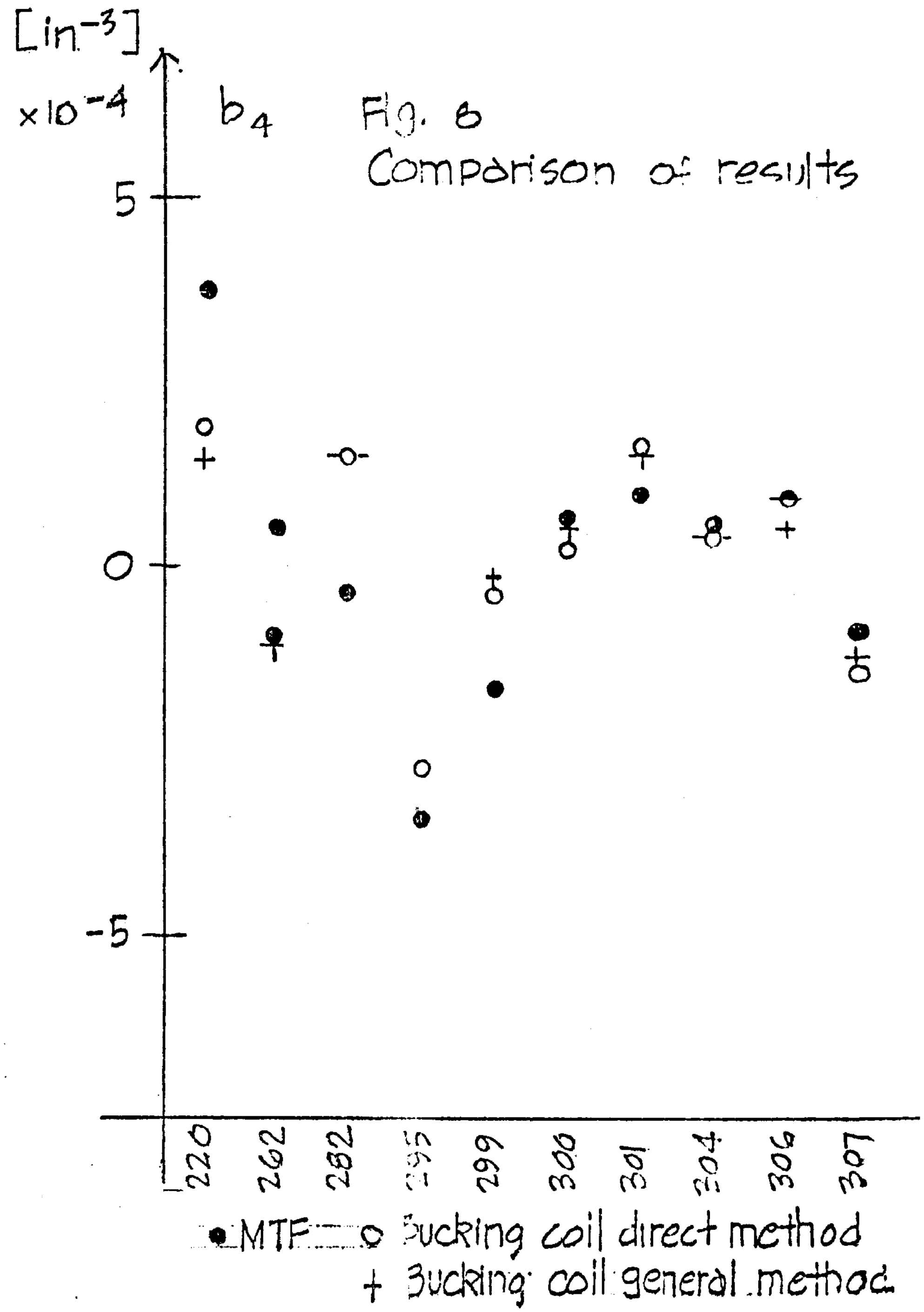


Fig. 6
Comparison of results

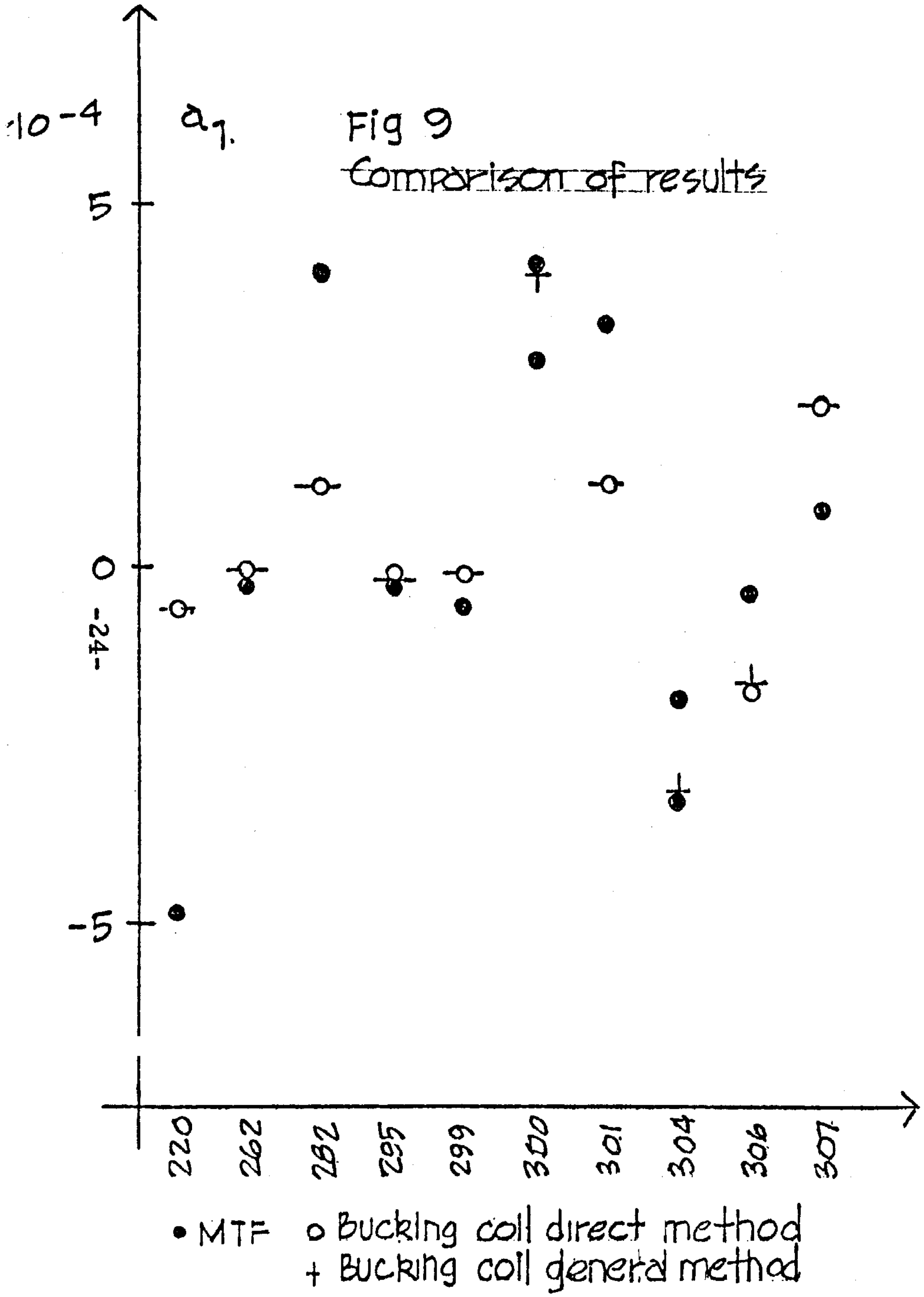


Fig 9
Comparison of results

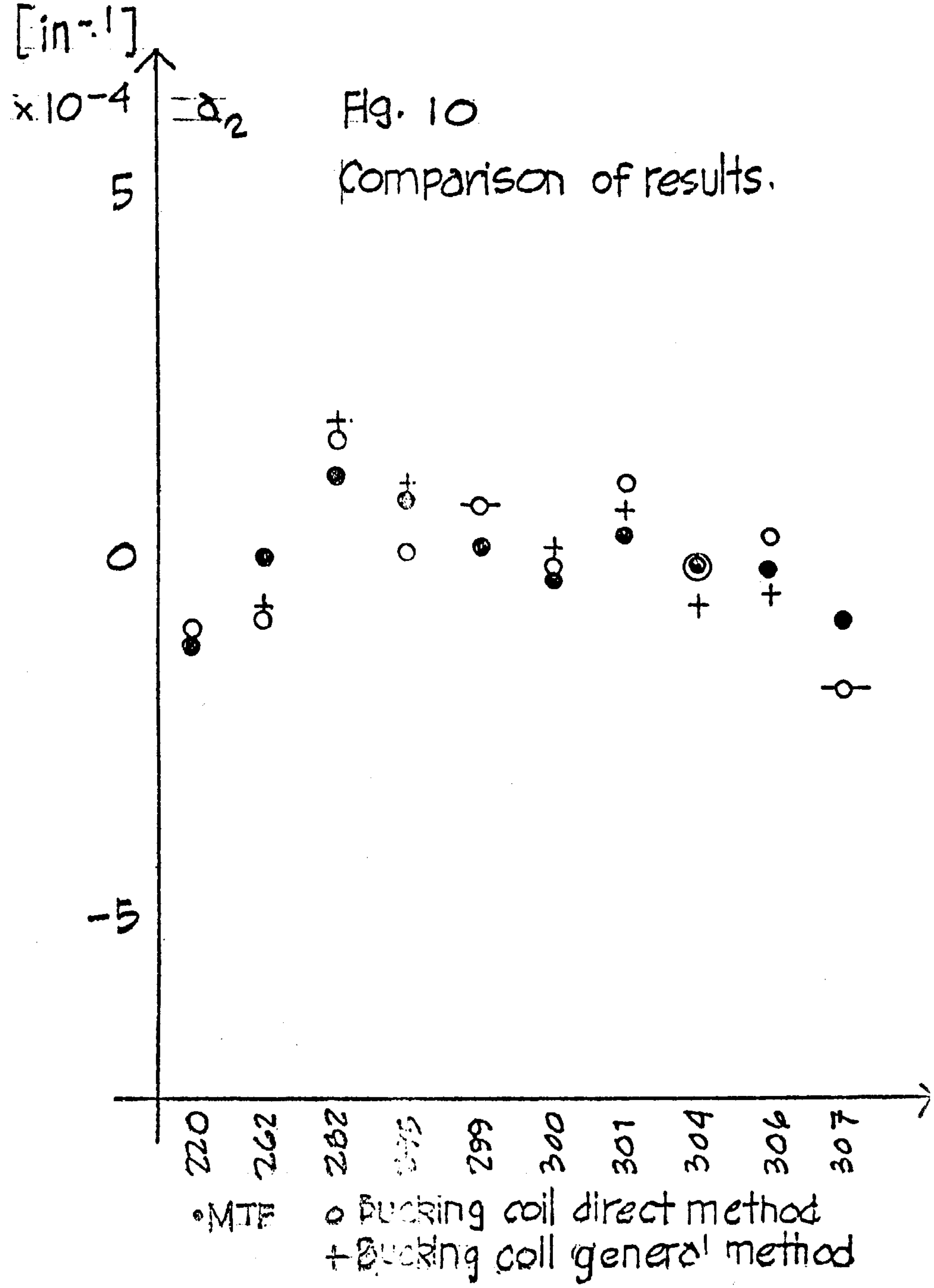
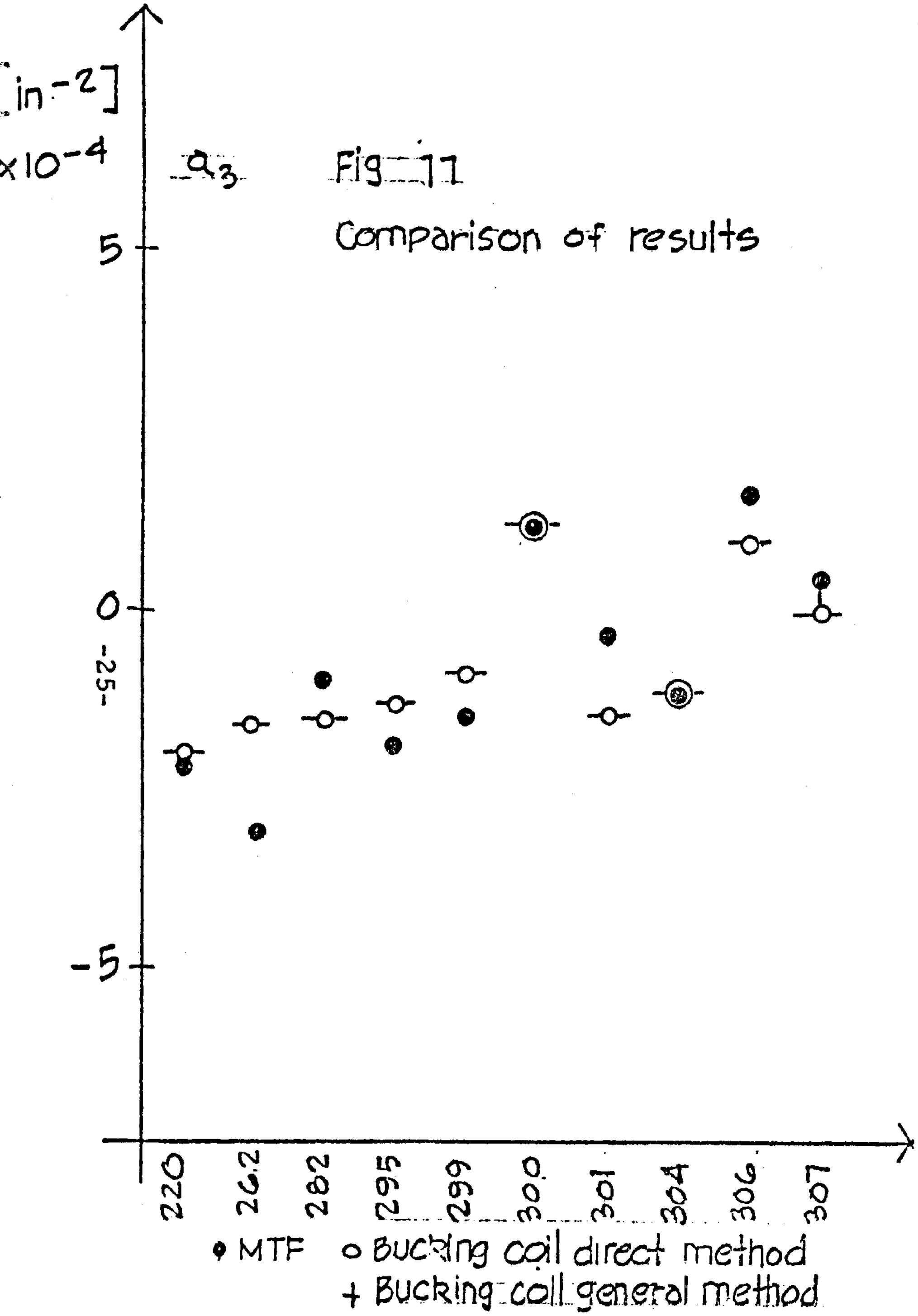


Fig. 10
Comparison of results.


[in^{-2}]
×10^{-4}
a_3
Fig 11
Comparison of results
5
0
-5
220
26.2
282
295
299
300
301
304
306
307
• MTF
○ Bucking coil direct method
+ Bucking coil general method

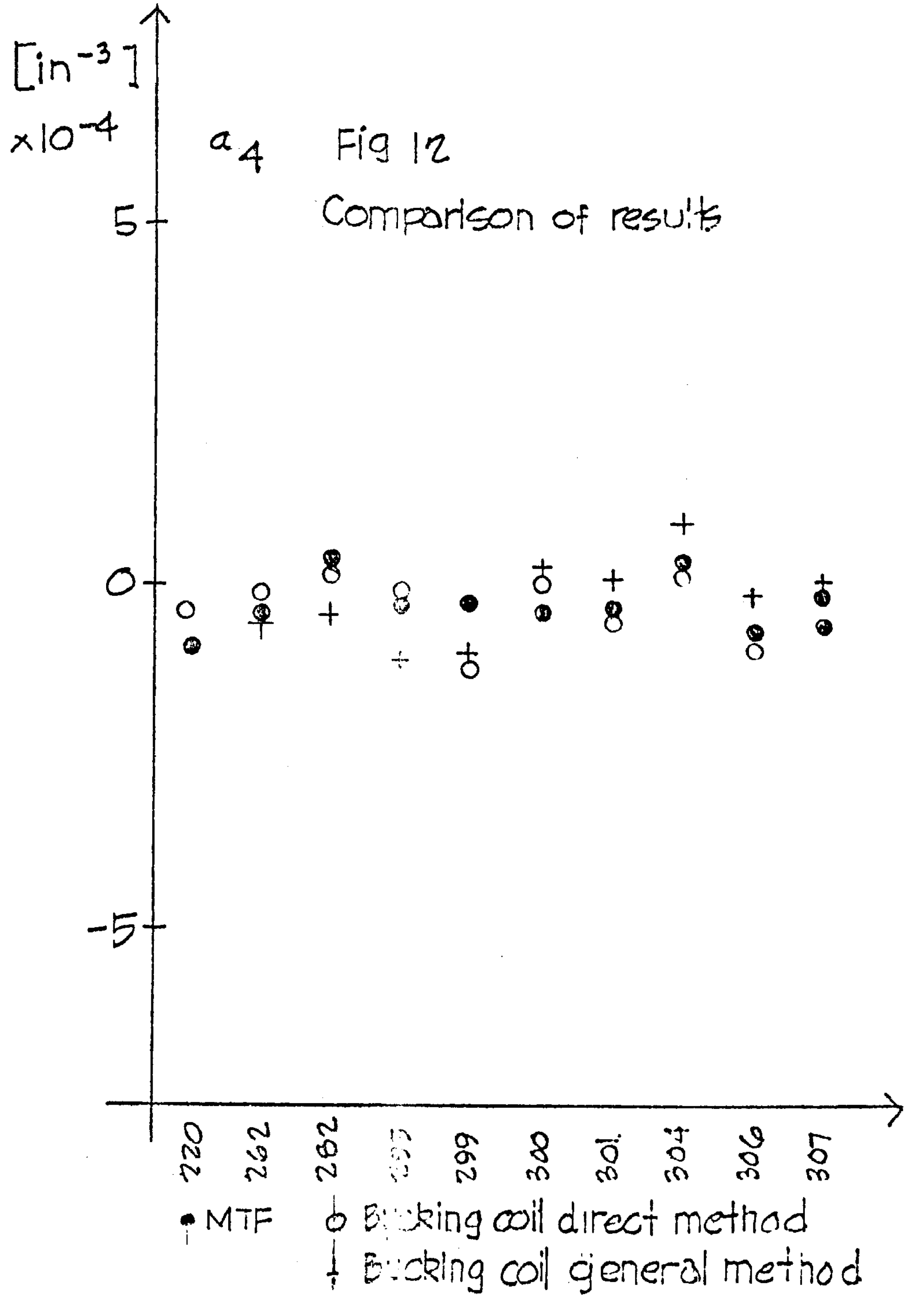

[in^{-3}]
×10^{-4}
a_4
Fig 12
Comparison of results
5
0
-5
220
262
282
295
299
300
301
304
306
307
• MTF
○ Bucking coil direct method
+ Bucking coil general method

Fig 13

Differences between MTF
and room temperature measurements
for normal quadrupole moments

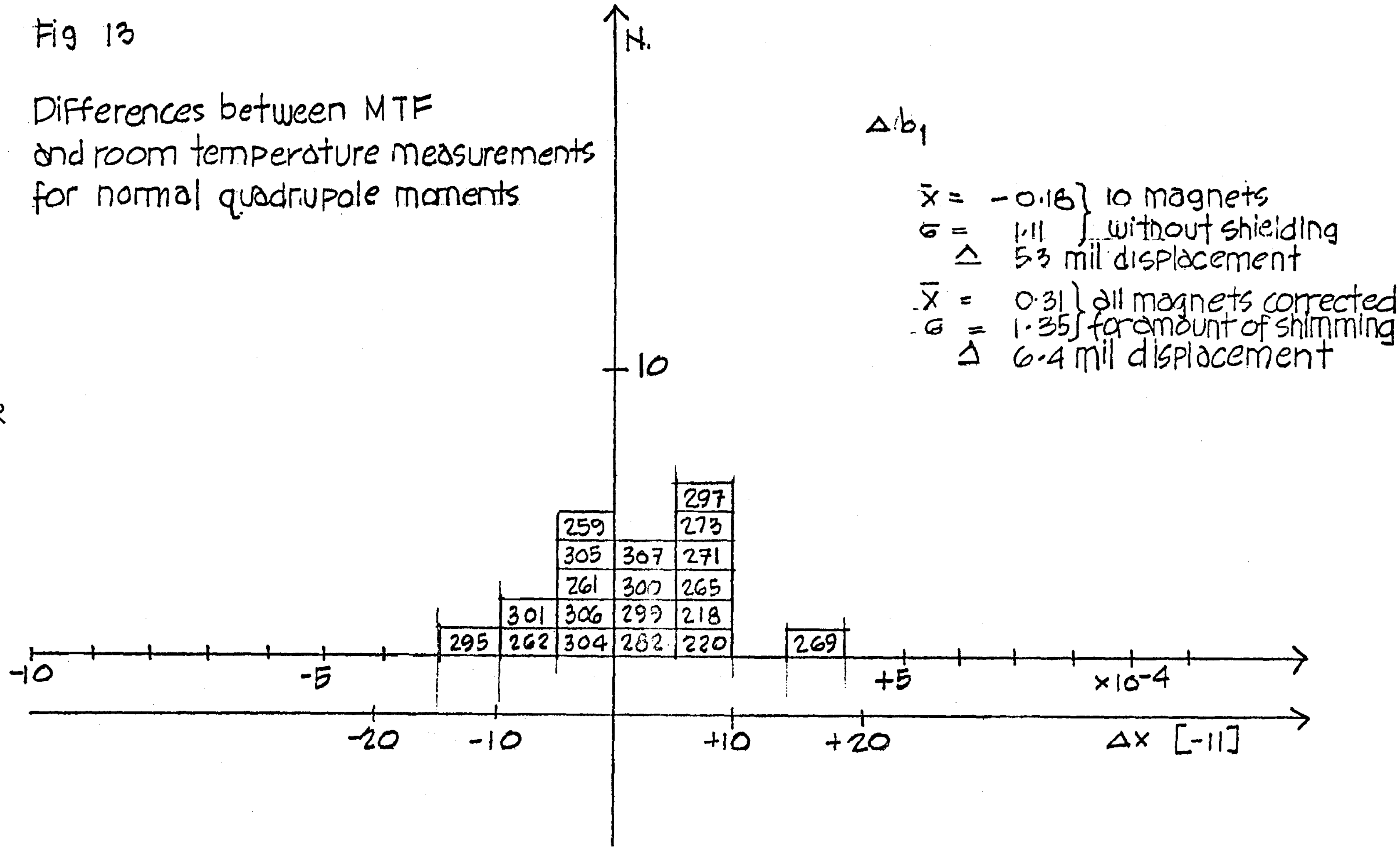
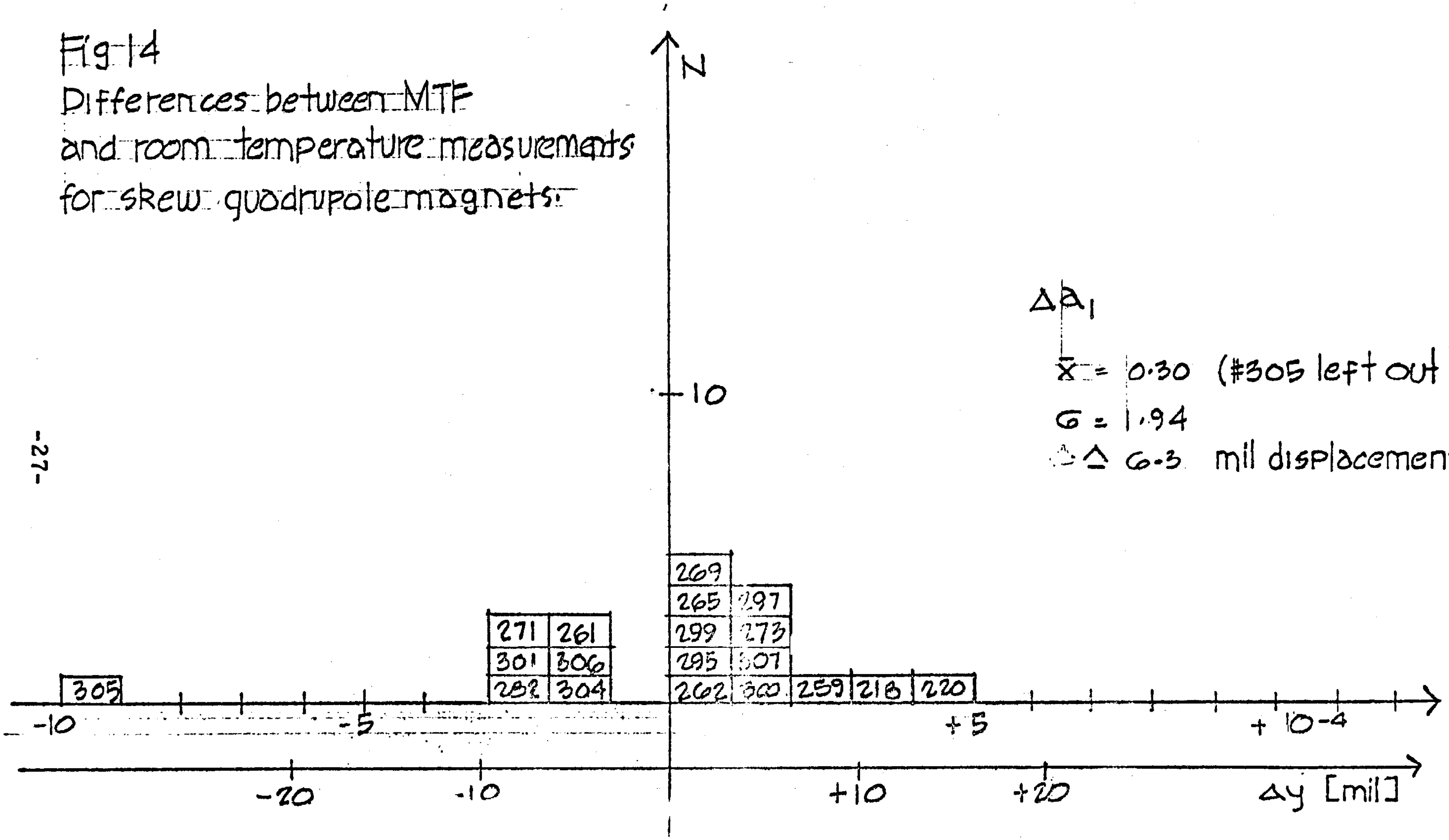


Fig 14
Differences between MTF
and room temperature measurements
for skew quadrupole magnets.

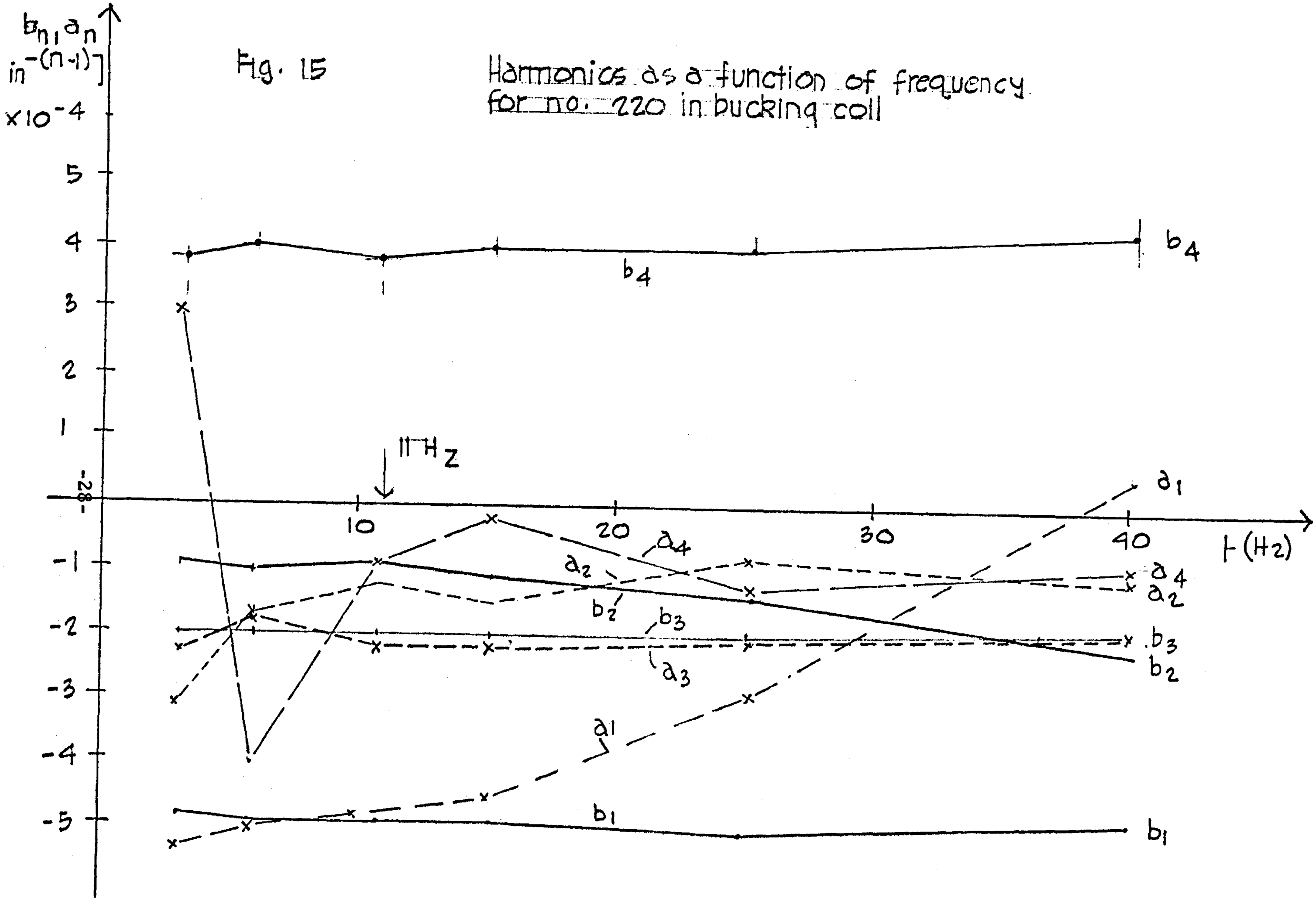


Δa_1

$\bar{x}$ = 0.30 (#305 left out)
σ = 1.94
≙ 6.3 mil displacement

Fig. 15

Harmonics as a function of frequency for no. 220 in bucking coil



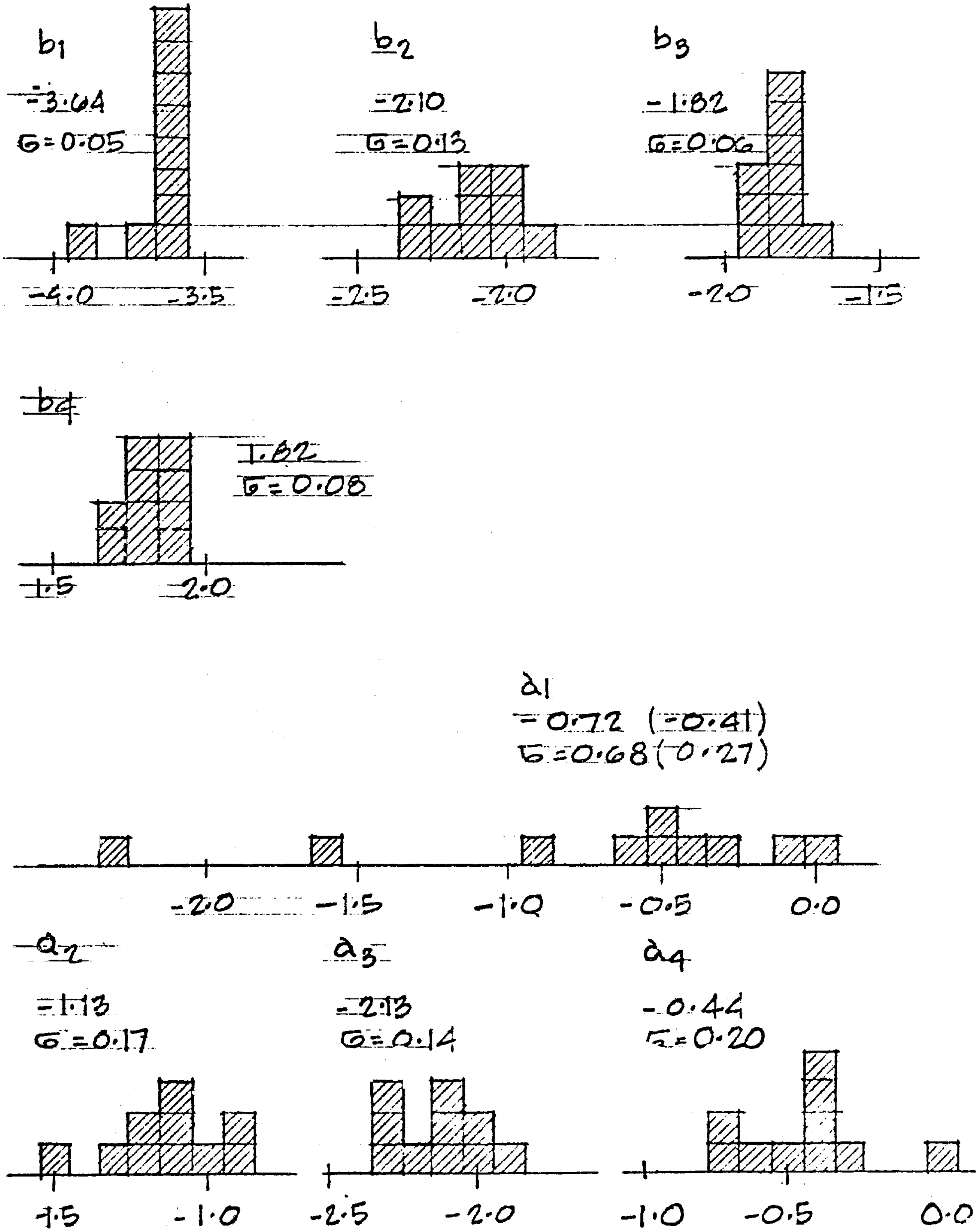


Fig 16: The reproducibility of harmonic measurements for magnet 220 (units = $[10^{-4} \text{ in}^{-(n-1)}]$)